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Quarterly Progress Report 2 | *Covering the Period 1 September to 30 November 1962*

OBJECTIVE AND DYNAMICAL STUDIES OF TROPICAL WEATHER PHENOMENA

Prepared for:

U.S. ARMY ELECTRONIC RESEARCH AND DEVELOPMENT LABORATORY
FORT MONMOUTH, NEW JERSEY

CONTRACT DA 36-039 SC-89092
PROJECT 3A99-27-025-09-00

STANFORD RESEARCH INSTITUTE

MENLO PARK, CALIFORNIA

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By: *R. M. Endlich* *R. L. Mancuso*

Objective: To carry out research leading to the development of objective methods of analyzing and forecasting tropical weather, and concerning the dynamics of tropical circulations.

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PURPOSE

The purpose of this research is to furnish knowledge that can be used in the development of objective methods of analyzing and forecasting tropical weather and in understanding the dynamics of tropical weather phenomena. It is planned that the objective techniques will be designed for electronic computation in order to gain speed and accuracy, and to reduce personnel requirements in an operational situation. The investigations are divided into the following tasks:

(1) Analyze the surface weather, the three-dimensional structure, the changes with time, and the movement, of selected cases of representative meteorological phenomena, by using conventional methods. If practicable, Tiros data will be included in the analysis.

(2) Investigate and, insofar as possible, develop objective analysis techniques applicable to tropical phenomena and compare the objective analyses with the analyses of Task (1) above.

(3) Utilizing the analyses of Tasks (1) and (2) above, carry out dynamical studies of such topics as the forces predominant in various phenomena, the conservation of fields of vorticity, divergence and deformation, and the importance of orography and low-level energy inputs.

ABSTRACT

During the second quarter, IBM card data for the Caribbean for the period 5-8 May 1959 were processed in the form of layer averages of wind components, height, temperature, and relative humidity. The averaged quantities were mapped by the computer, and subjective analyses were partially completed. A computer program for obtaining a streamfunction was completed. The streamfunction is made to fit observed winds, while observed heights are used as an initial guess. No boundary conditions are required. A preliminary analysis indicates that the results are quite satisfactory. Analyses of computed values of vorticity, divergence, and vertical motion were also begun, and average magnitudes of these quantities were determined.

I PUBLICATIONS, LECTURES, REPORTS, AND CONFERENCES

Publications, Lectures, and Reports

On 14 September 1962, a paper entitled "Some Applications of Computers in Tropical Analysis" was presented by R. M. Endlich at the Fourth Conference on Applied Meteorology at Fort Monroe, Virginia. This paper summarized the approach which is being pursued in the contractual work and followed the material presented in the First Quarterly Progress Report.

Conferences

The Chief Signal Officer, Major General E. Cook, visited the Institute on 5 September 1962. During his visit, Mr. Endlich and Dr. Ligda outlined the contractual work and discussed tropical meteorology with him.

On 12 September 1962, a discussion and review of the contractual work took place at Fort Monroe between Mr. Endlich of SRI, and Mr. Raymond Bellucci and Mr. Joseph Walsh of the Atmospheric Physics Branch, USAERDL.

II FACTUAL DATA

A. Task 1

The IBM card data for the Caribbean for the period 5-8 July 1959 were processed in the form of layer averages of height, temperature, relative humidity, and wind components. Analyses of the various quantities (drawing of isolines) are partially completed. Examples of layer-averaged winds and heights are shown in Figs. 1 and 2, and will be discussed in more detail in Sec. II-B. A point of considerable interest is that the layer-averaged humidity fields (see Fig. 3) consist of fairly large, regular patterns. It is believed that this fact will be important in analysis of clouds and precipitation and possibly also in estimating vertical motions from wind and humidity data. Since the analyses for the entire series are not complete, further discussion will be deferred to the next quarterly report.

B. Task 2

In regard to the development of objective analysis techniques, a number of basic computer programs for the Caribbean have been completed. The programs are indicated in Fig. 4. It is believed that they provide a means of rapidly obtaining values of most quantities of meteorological interest. Output can be in tabular form or printed at station locations (i.e., mapped).

In the First Quarterly Status Report, the need for an objective, numerical streamfunction to replace conventional subjective streamlines was discussed. During the present quarter, a machine program for computing a numerical streamfunction was completed. The results to date are very satisfactory. Since we anticipate that the technique will be described fully in a future scientific report, only a summary will be included at the present time. The horizontal wind vector $\mathbf{V}$ is represented by a streamfunction $\overset{*}{\psi}$ as follows:

$$\mathbf{V} = (g/f)\ (\mathbf{k} \times \nabla\overset{*}{\psi}) \qquad (1)$$

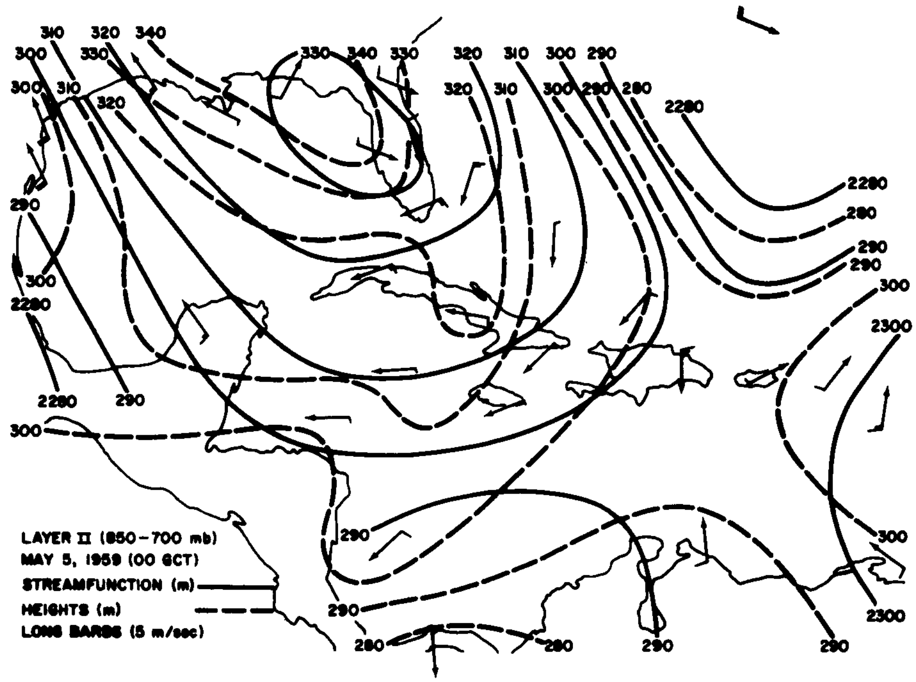

FIG. 1 WINDS, HEIGHTS, AND STREAMFUNCTION IN LAYER II (850-700 mb) AT 00 GCT, 5 MAY 1959

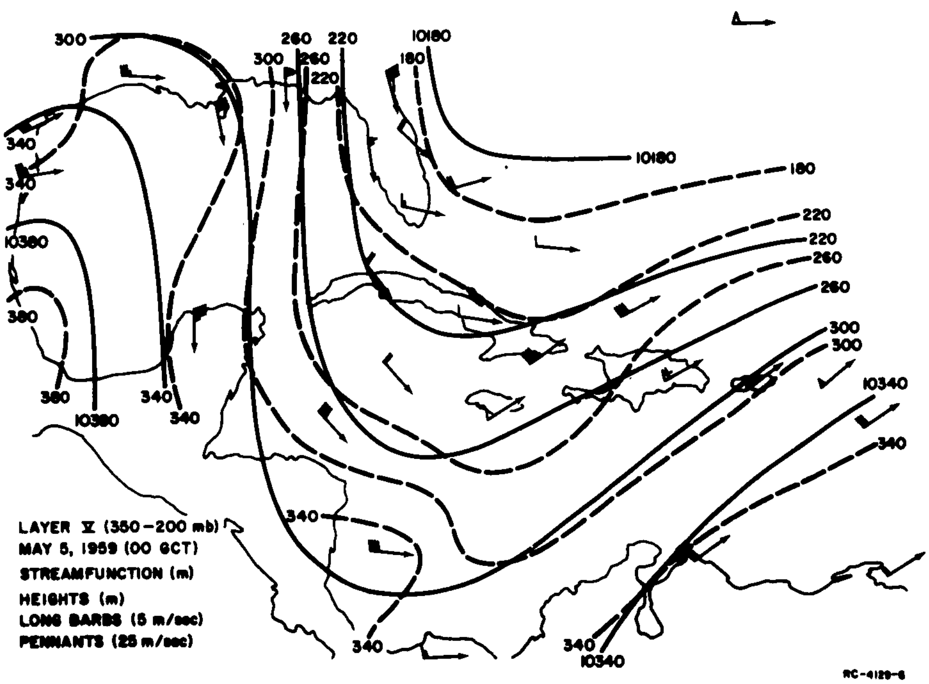

FIG. 2 WINDS, HEIGHTS, AND STREAMFUNCTIONS IN LAYER V (350-200 mb)

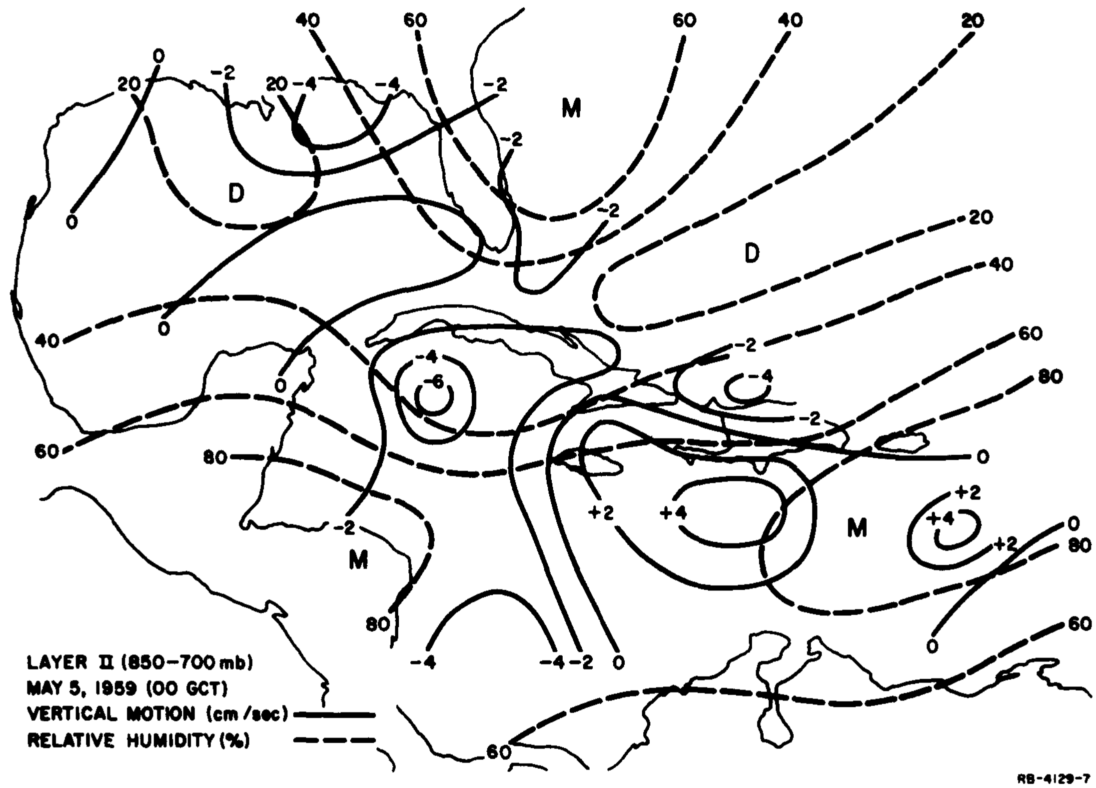

FIG. 3 RELATIVE HUMIDITY IN LAYER II, AND VERTICAL MOTIONS AT 700 mb

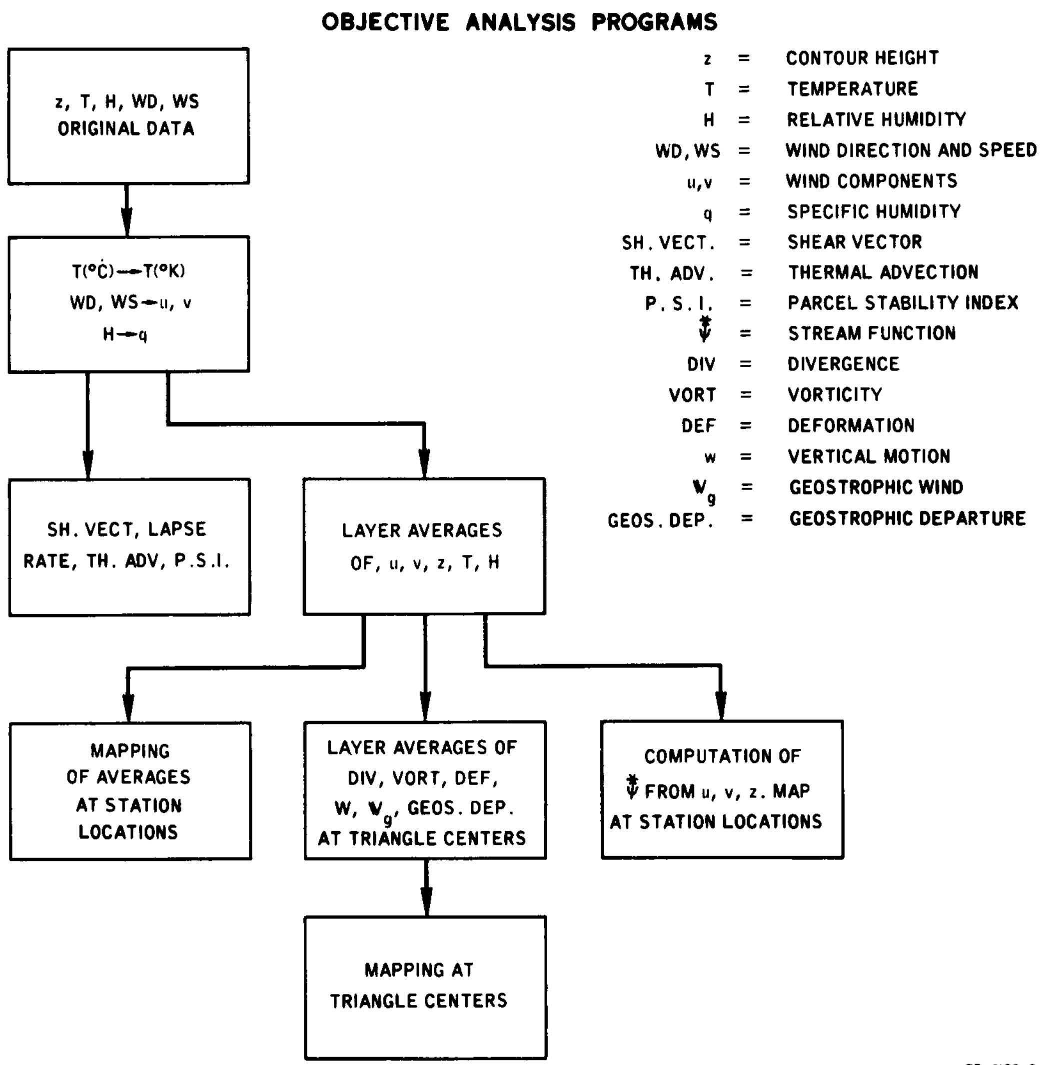

FIG. 4 FLOW DIAGRAM OF COMPUTATIONS

where $\overset{*}{\psi}$ has the units of meters.[†] It is assumed that divergent wind components can be suppressed by an areal averaging process. The equations relating wind components and the streamfunction are

$$u = -\ (g/f)\ (\partial\overset{*}{\psi}/\partial y), \qquad v = (g/f)\ (\partial\overset{*}{\psi}/\partial x) \quad . \tag{2}$$

Since wind observations are the primary data used in tropical analysis, observed values of u and v are used to determine values of $\partial\overset{*}{\psi}/\partial y$ and $\partial\overset{*}{\psi}/\partial x$, and thence values of $\overset{*}{\psi}$. Consider a pair of stations separated by distance increments δx and δy. The streamfunction difference between them is

$$\delta\overset{*}{\psi} = (\partial\overset{*}{\psi}/\partial x)\ \delta x + (\partial\overset{*}{\psi}/\partial y)\ \delta y = (f/g)\ (v\delta x - u\delta y) \tag{3}$$

where the appropriate values of u, v, and f are the average values along a line joining the stations. These averages may be taken as $(u_o + u_i)/2$, $(v_o + v_i)/2$, and $(f_o + f_i)/2$, where the subscript o denotes values at the station of interest and i denotes values at a neighboring station. Then Eq. (3) becomes

$$\overset{*}{\psi}_o = \overset{*}{\psi}_i + \frac{(f_o + f_i)}{2g}\left[\frac{(v_o + v_i)\ (x_o - x_i)}{2} - \frac{(u_o + u_i)\ (y_o - y_i)}{2}\right] \quad . \tag{4}$$

An equation of this form may be obtained between station o and each of its n neighbors--i.e., i = 1, 2, ..., n.

A reasonable estimate of $\overset{*}{\psi}_o$ might be taken as the average of the individual estimates--i.e.,

$$\overset{*}{\psi}_o = \frac{1}{n}\sum_{i=1}^{n}\overset{*}{\psi}_i + \frac{1}{4gn}\sum_{i=1}^{n}(f_o + f_i)\ [(v_o + v_i)\ (x_o - x_i) - (u_o + u_i)\ (y_o - y_i)] \quad . \tag{5}$$

[†]Since f approaches zero as the equator is approached, it is desirable to avoid the use of f in equatorial regions. This can be done simply by setting $\mathbf{V} = \mathbf{k} \times \nabla\psi$ (where ψ has the units $m^2 sec^{-1}$) or by placing a fictitious lower limit on f.

However, experience in objective analysis in mid-latitudes has shown that observations should be weighted inversely with their distance from the point of interest.[1,2†] Therefore, one estimate $(\overset{*}{\psi}_o)_1$ is obtained by considering all stations lying within a radius of 5 degrees of latitude and a second estimate $(\overset{*}{\psi}_o)_2$ is obtained by considering stations lying between 5 and 9 degrees of latitude away. The two estimates are then combined as

$$\overset{*}{\psi}_o = \mu_1 \, (\overset{*}{\psi}_o)_1 + \mu_2 \, (\overset{*}{\psi}_o)_2 \tag{6}$$

where μ_1 and μ_2 are weighting factors presently set at 0.8 and 0.2. The entire field of observing stations is scanned in this manner, producing adjusted values of $\overset{*}{\psi}$ which are immediately substituted for the previous ones according to the Liebmann iteration process. The initial values of $\overset{*}{\psi}_i$ at each station are taken equal to the reported heights Z_i. Several scans of the field are performed until nearly convergent values of $\overset{*}{\psi}$ are obtained. The average of the computed values of streamfunction remains approximately equal to the average of the heights used as the initial guess. It was assumed at the outset that the divergent wind components would be suppressed. Since the computation of $\overset{*}{\psi}$ at each station depends upon several winds out to a radius of 9° of latitude, the divergent features are automatically suppressed by the computational procedure.

The direct streamfunction computation described above appears to have several advantages over other possible formulations. The general approach is simple in principle. The use of boundary conditions is avoided. It is not necessary to use a rectangular grid. The computed values of $\overset{*}{\psi}$ can be compared directly with observed heights. Wind estimates made from satellite data could be utilized in the system. At present, total machine time for computing $\overset{*}{\psi}$ in each of six layers and printing out the computed values in mapped form is about 10 minutes using the Burroughs 220 computer.

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†References are listed at the end of the report.

A qualitative assessment of the computed streamfunction can be made by inspection of Figs. 1 and 2, which show layered-averaged winds, heights, and streamfunction. Layers II and V are representative of the lower and upper troposphere, respectively. Note the agreement of winds and streamfunction in contrast to the lack of reasonable relationships between winds and height contours. (Twelve hours after the charts shown, the correspondence of heights and winds was even less satisfactory.) A preliminary quantitative evaluation can be made from the information contained in Table I. The first quantity is the root-mean-square (RMS) value of the observational error in height (Z). The second quantity is the RMS value of the difference between Z and the streamfunction $\overset{*}{\psi}$. The other four quantities are RMS values of 12-hour and 24-hour changes of height and streamfunction. It is interesting to note that the RMS 12-hour height changes exceed the 24-hour changes, contrary to expectations.

Table I

COMPARISON OF HEIGHT (Z) AND STREAMFUNCTION ($\overset{*}{\psi}$)
DURING THE PERIOD 00 GCT, 5 MAY 1959 TO 00 GCT, 6 MAY 1959
IN THE CARIBBEAN (30 STATIONS)

Layer II	RMS Error of Z	≈	5 m
	RMS (Z - $\overset{*}{\psi}$)	=	9 m
	RMS 12-hour height change	=	13 m
	RMS 24-hour height change	=	9 m
	RMS 12-hour $\overset{*}{\psi}$ change	=	5 m
	RMS 24-hour $\overset{*}{\psi}$ change	=	9 m
Layer V	RMS Error of Z	≈	20 m
	RMS (Z - $\overset{*}{\psi}$)	=	27 m
	RMS 12-hour height change	=	31 m
	RMS 24-hour height change	=	26 m
	RMS 12-hour $\overset{*}{\psi}$ change	=	15 m
	RMS 24-hour $\overset{*}{\psi}$ change	=	17 m

The reason for this result has not yet been investigated. However, the main point of interest is a comparison of streamfunction changes and height changes. The smaller values of streamfunction changes indicate that streamfunction is a considerably more persistent quantity than height. In fact, in Layer V the RMS streamfunction change is slightly smaller than the RMS error of height. These results are very encouraging.

As indicated in Fig. 4, values of vorticity, divergence, deformation, and vertical motion have been computed from wind data by use of the triangle technique.[3] Examples of the computed values in Layers II and V are shown in Figs. 5 and 6 for purposes of illustration. In Layer II, the relative vorticity (solid lines) is negative in the anticyclone (Fig. 1) and positive in two centers related to the trough in the southeastern portion of the Caribbean. The divergence field contains four centers of size sufficient to insure that they are real. The vertical motion at the top of Layer II is shown as part of Fig. 3. The vertical motion is predominantly negative (downward) except in the region of the trough, and appears to have a reasonable correspondence with the humidity field.

In Layer V, the vorticity field (Fig. 6) consists of four main centers which appear to characterize important features of the flow shown in Fig. 2. The northwesterly jet lying west of Florida has cyclonic relative vorticity on the low-pressure side and anticyclonic vorticity on the other side. The streamline trough is a region of cyclonic vorticity, and the south side of the jet lying east of the trough is a region of anticyclonic vorticity. The divergence field in Layer V contains a major center of convergence over the Gulf of Mexico in advance of an isotach maximum. The other centers are apparently related to the trough and jet stream.

At this time we have not attempted to evaluate the computed values of divergence, vorticity, etc., nor to determine their proper use in analysis and forecasting. These subjects require a considerable amount of further study.

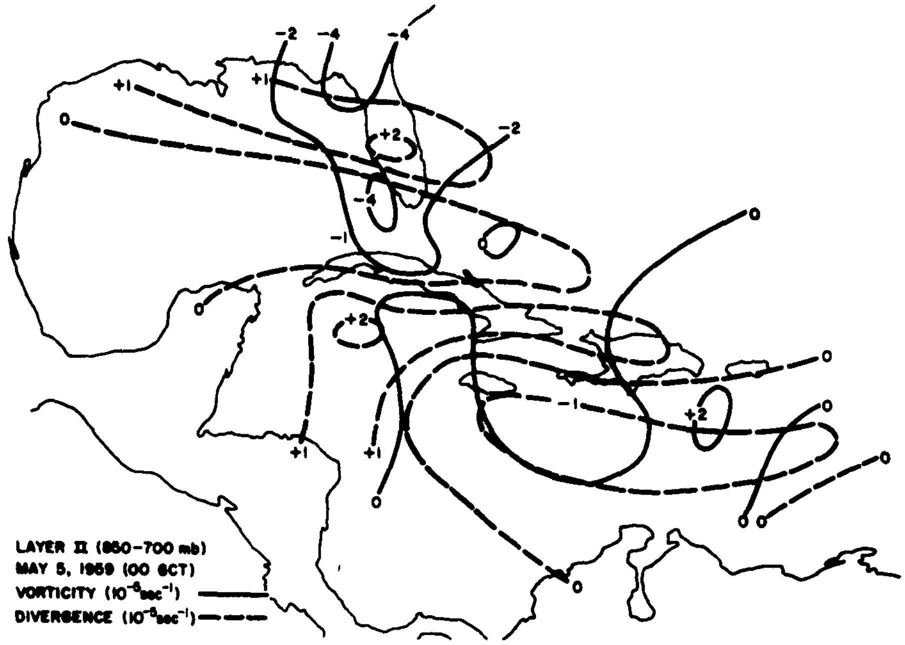

FIG. 5 RELATIVE VORTICITY AND DIVERGENCE IN LAYER II

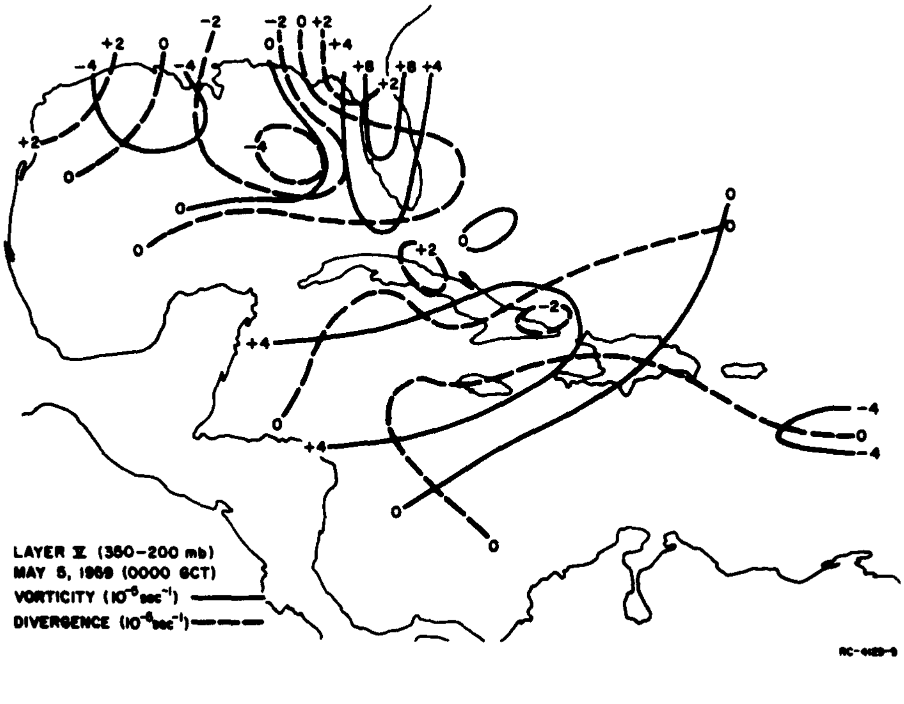

FIG. 6 RELATIVE VORTICITY AND DIVERGENCE IN LAYER V

C. Task 3

The average magnitudes of several terms important in dynamical equations have been computed from data for 5-6 May 1959 and 28 July 1959. Discussions at the Conference on Tropical Meteorology[4] revealed differing opinions regarding these magnitudes. Table II lists the results of our computations for the Caribbean.

Table II

AVERAGE MAGNITUDES OF DYNAMICAL TERMS

	Layer II	Layer V
Divergence	0.9×10^{-5} sec^{-1}	1.5×10^{-5} sec^{-1}
Vorticity	1.1×10^{-5}	3.0×10^{-5}
Resultant Deformation	1.4×10^{-5}	3.2×10^{-5}

It is rather surprising that these values are nearly as large as typical values computed for mid-latitudes.[3] This may be due in part to the presence of unusually active circulations in the Caribbean during the periods under investigation.

Consideration has been given to several other topics, including the determination of synoptic-scale vertical motions from relative humidity changes experienced by parcels, objective techniques of kinematical forecasting, methods of applying the vorticity equation in the tropics, and use of the conventional balance equation to determine Z from $\overset{*}{\psi}$. These topics will be discussed in later reports.

III PROGRAM FOR THE NEXT QUARTER

The analyses for the period 5-8 May 1959 will be completed and a major effort will be expended in evaluation of the objectively computed streamfunction, divergence, vertical motions, etc. The effects of scale (areas considered) upon computed values will be investigated. Further studies related to dynamical quantities will be carried out. It is also expected that a scientific report describing the streamfunction computation will be begun. At this time, no definite plans for travel during the quarter have been made.

IV PERSONNEL

Name	Time Devoted to Project this Quarter
M. G.H. Ligda, Project Supervisor	Approximately 8 hours
R. M. Endlich, Project Leader	Approximately 175 hours
R. L. Mancuso, Research Meteorologist	Approximately 380 hours
J. R. Clark, Research Meteorologist	Approximately 45 hours
B. Crowell, Meteorological Aide	Approximately 55 hours
J. Weaver, Meteorological Aide	Approximately 20 hours

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2. Cressman, G. P., "An Operational Objective Analysis System," Monthly Weather Review 87, No. 10, pp. 367-374 (1959).

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